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DOI
10.1088/1742-6596/718/5/052018

Publication date
2016

Document Version
Final published version

Published in
Journal of Physics: Conference Series

Gamma-ray and neutrino diffuse emissions of the Galaxy above the TeV

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Abstract. Conventional cosmic ray propagation models face problems reproducing the diffuse γ-ray spectrum measured by Fermi-LAT over the entire sky. Those models also fail to smoothly connect Fermi-LAT results with data above the TeV as those taken by Milagro in the inner Galactic plane. In this contribution we show that a representative model adopting a spatial dependent rigidity scaling of the diffusion coefficient can reproduce all those experimental results without spoiling the consistency with local cosmic-ray measurements. We use the same model to compute the diffuse neutrino emission of the Galaxy and compare it with IceCube and ANTARES results.

1. Introduction

Cosmic-ray (CR) transport in the Galaxy and secondary γ-ray and neutrino diffuse emission are conventionally modeled assuming that charged particles undergo statistically homogeneous and isotropic diffusion due to their scattering onto the Galactic magnetic field fluctuations. This amounts to treat diffusion in terms of a spatially independent coefficient D which only depends on the particle rigidity. Although this simplified approach provides a reasonable description of a wide number of experimental data it should be taken in mind that charged CR provide only a relatively local probe of the Galactic population. For example the Boron to Carbon ratio, which is generally used to tune the relevant propagation parameters, is expected to be determined by processes taking place within few kpc from the Earth. Therefore this kind of observables is not sensitive to the CR population in the more inner regions of the Galaxy where most of γ-ray and neutrinos are expected to be produced. Interestingly, although such *conventional* picture accounts for the main features of the γ-ray Galactic diffuse emission, several anomalies suggest that some main ingredients may be missing in that approach.

We start noticing that the Fermi-LAT collaboration [1] found an excess in the γ-ray diffuse emission above 10 GeV in the inner Galactic Plane (GP) with respect to the predictions of their GALPROP [2, 3] based conventional models tuned to reproduce local CR observables. Interestingly, Fermi data seem to favor a longitude dependent spectral index of the γ-ray emission [4]. These results have been confirmed by an independent analysis performed by some of the authors of this contribution [5]. In that paper it was also shown that a CR propagation model implemented with the DRAGON code [6, 7], featuring a radial dependence for both the rigidity scaling index δ of the diffusion coefficient and the convective wind, provides a much better description of Fermi results (see below for more details about that model).

In this contribution (see also [8]) we will show that the very same model offers a viable solution to another long standing anomaly at higher energies. Indeed, while *conventional* CR propagation models cannot explain the large γ-ray flux measured by the Milagro observatory from the inner GP region ($|b| < 2°$, $30° < l < 65°$) at 15 TeV median energy [9] the KRA$_\gamma$ model proposed in [5] matches Milagro result. Since the γ-ray diffuse emission along the GP is mostly due to hadronic scattering, those results have a relevant implications for the computation of the neutrino emission of the Galaxy. This is a hot subject in light of recent IceCube detection of 37 extraterrestrial neutrinos above ~ 30 TeV [10, 11, 12]. [1] A significant Galactic contribution – up to $\sim 50\%$ – to the IceCube is allowed by the angular distribution of IceCube events [14]. In fact, a recent IceCube analysis [15] suggest the presence of a larger and softer neutrino spectrum in the southern hemisphere [15] which might be explained in those terms.

After reporting the main features of the KRA$_\gamma$ model in Sec.2, in Sec.3 we will show how that model also reproduces Milagro γ-ray results; then in Sec.4 we will present our prediction for the Galactic neutrino emission and compare it with IceCube and ANTARES results.

2. The KRA$_\gamma$ setup

The model proposed in [5] assumes that the exponent δ determining the rigidity dependence of the CR diffusion coefficient

$$D(R, z, \rho) = D_0 \left(\rho/\rho_0\right)^{\delta(R)} \exp(z/z_t) \quad (1)$$

has the following Galactocentric radial dependence: $\delta(R) = AR + B$ where $A = 0.035$ kpc^{-1} and $B = 0.21$ so that $\delta(R_\odot) = 0.5$. Concerning the vertical dependence of the diffusion coefficient we assume $z_t = 4$ kpc (we checked that our results do not change significantly considering larger values of z_t). This behaviour may have different physical interpretations, e.g. a smooth transition between a dominant parallel escape along the poloidal component of the regular Galactic magnetic field (in the inner Galaxy, where δ is lower) and a perpendicular escape with respect to the regular field lying in the plane (in the outer Galaxy, where the scaling is steeper). The model also adopts a convective wind for $R < 6.5$ kpc with velocity $V_C(z)\hat{z}$ (z is the distance from the GP) vanishing at $z = 0$ and growing as $dV_c/dz = 100$ km s^{-1} kpc^{-1} as motivated by the X-ray ROSAT observations.

The observed γ-ray spectra at both low and mid Galactic latitudes, including the Galactic center, are reproduced by this model without spoiling local CR observables: proton, antiproton and Helium spectra, B/C and ^{10}Be/^{9}Be ratios. Moreover, this scenario naturally accounts for the radial dependence in the CR spectrum found by the Fermi collaboration [4]. We implement the setup with DRAGON, a numerical code designed to compute the propagation of all CR species [6, 7] in the general framework of position-dependent diffusion.

Concerning the p and He spectral hardening inferred from PAMELA [16] - recently confirmed by AMS-02 [17] - and CREAM [18] data above ~ 250 GeV/n, we consider two alternatives. *1) Local hardening* as could be originated by nearby supernova remnants. *2) Global hardening* as it may be originated by a spectral feature in the rigidity dependence of CR source spectra or in the diffusion coefficient (here we only consider the former case as both scenarios have the same effect on the γ-ray diffuse emission). In both cases we assume that above 250 GeV/n the CR source spectra extend steadily up to an exponential cutoff at the energy $E_{\rm cut}$/nucleon. We consider two representative values of this quantity, namely $E_{\rm cut} = 5$ and 50 PeV which - for the KRA$_\gamma$ setup

[1] More recently, a preliminary analysis [13], based on four years of data, rose the total number of high-energy starting events (HESE) to 54.

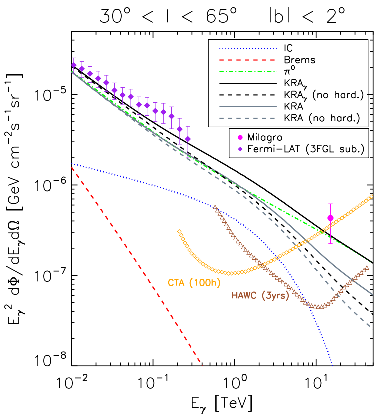

Figure 1. The diffuse emission γ-ray spectrum from the inner Galactic plane ($|b| < 2°$, $30° < l < 65°$) computed for the reference models considered in this Letter is compared with Fermi-LAT and Milagro data. The expected sensitivity of HAWC and CTA are reported. The spectral components are shown for the KRA$_\gamma$ model only. The Fermi-LAT data points refer to 5 years of data, within the event class ULTRACLEAN according to Fermi tools v9r32p5.

- match CREAM p and He data and roughly bracket KASCADE [19] and KASCADE-Grande data [20].

We will refer to this model as "KRA$_\gamma$" since it is tuned on γ-ray data. In the next sections this model will be compared with a representative conventional model (KRA) with $\delta = 0.5$ in the whole Galaxy and no convection which also reproduces local CR observable and predicts a γ-diffuse emission practically coincident with that predicted by the Fermi benchmark model based on `GALPROP`.

3. The diffuse γ-ray spectrum above the TeV

It was shown in [5] that the KRA$_\gamma$ model provides a good fit of the γ-ray diffuse emission measured by Fermi-LAT all over the sky, in particular towards the inner GP region. In [8] we extended that computation above the TeV. Starting from the propagated proton and Helium distributions – heavier nuclei give a negligible contribution – we computed the hadronic emission integrating the expression of the γ-ray emissivity [21] along the line-of-sight. The model also includes CR electrons matching PAMELA and AMS-02 data which are accounted for in order to compute the Inverse-Compton contribution (subdominat on the GP) to the total γ-ray flux.

Our results are shown in Fig. 1. As mentioned in the above, a representative conventional model (KRA) cannot account for the flux measured by Milagro from the inner GP at 15 TeV even accounting for the CR spectral hardening required to match PAMELA and CREAM data. The KRA$_\gamma$ setup, instead, is more successful, especially if a global hardening is assumed. This is a remarkable result since: *1)* it supports the KRA$_\gamma$ model in a higher energy regime; *2)* it provides the first consistent interpretation of Milagro and Fermi-LAT results (an *optimized* model was proposed to account for the EGRET GeV excess [22], and came out to reproduce Milagro result as well, but was subsequently excluded by Fermi-LAT [23]), and *3)* it reinforces the arguments in favor of a non-local origin of the hardening in the CR spectra above 250 GeV.

Interestingly the KRA$_\gamma$ model also reproduces the high-energy diffuse γ-ray spectrum measured by H.E.S.S. in the Galactic ridge region ($|l| < 0.8°$, $|b| < 0.3°$) in terms of CR scattering with the dense gas in the central molecular zone without the need to invoke the contribution of sources to that region [24] and without further tuning (see [25] for more details). Although this is a very small region with respect to those considered here, this result may be interpreted as a valuable check of our model in a region not covered by Milagro. Moreover, we checked that the KRA$_\gamma$ model is also compatible with ARGO-YBJ results in the window $65° < l < 85°$ and $|b| < 5°$ and CASA-MIA measurements at higher Galactic longitudes.

4. The neutrino emission of the Galaxy.

The hadronic component of the diffuse γ-ray emission discussed in the previous section is accompanied by a neutrino emission of similar intensity. We computed its spectrum as described in [26, 8] accounting for neutrino oscillations which effect is to almost equally redistribute the composition among the three flavors.

Since also in this case the emission is expected to be maximal in the inner GP region, we first present our results for the window $|l| < 30°$ and $|b| < 4°$. For this region the ANTARES collaboration [27] recently released an upper limit on the muon neutrino flux based on the result of an unblinding analysis regarding the events collected between 2007 and 2013 in the energy range $[3 \div 300]$ TeV [28].

In Fig. 2 we compare the ν_μ flux computed with the KRA (conventional model) and KRA$_\gamma$ setups with that experimental constraint. First of all we notice the large enhancement (almost a factor of 5 at 100 TeV) obtained with the KRA$_\gamma$ model respect to the conventional scenario. Indeed, while – in agreement with previous results – we find that the flux corresponding to the KRA model may require long time of observation even by the KM3NeT observatory [29], our prediction for the KRA$_\gamma$ model is instead well above the sensitivity reachable by that experiment in 4 years and it is almost within the ANTARES observation capabilities. Interestingly, our result is in good agreement with the maximal flux which we inferred from the fraction of IceCube HESE events compatible with that region. A good agreement with IceCube results is also found on the whole Galactic plane (see e.g. Fig. 1 in [30]).

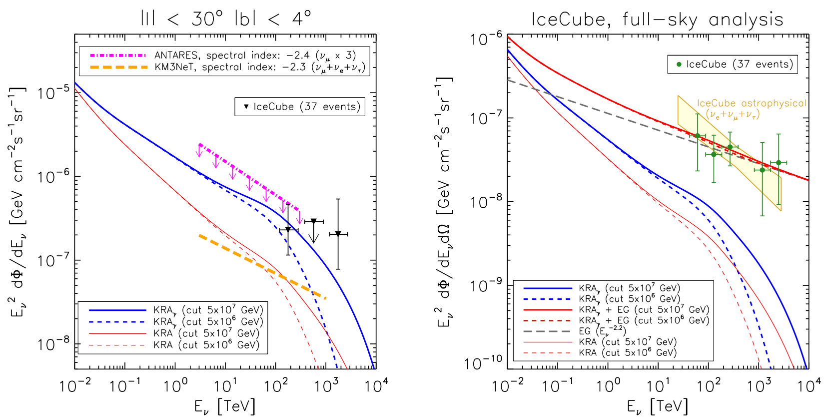

Figure 2. *Left panel*: Neutrino spectra(all flavors, both neutrinos and antineutrinos) in the inner Galactic plane region computed for the conventional KRA and the novel KRA$_\gamma$ models for two different cutoff of CR primaries. We also show the maximal flux, estimated considering 3 years of IceCube HESE events, the constraint from ANTARES experiment as well as the deduced sensitivity of the future Mediterranean observatory KM3NeT after 4 years of livetime. *Right panel*: The full-sky neutrino spectrum for the same models (with global CR hardening only); the best-fit isotropic component (representative of the Extra-Galactic flux) as inferred from the IceCube muon neutrino in the Northern hemisphere [15]; the sum of the latter and the KRA$_\gamma$. The models are compared with the 68% confidence region for the IceCube astrophysical neutrino flux obtained with a maximum-likelihood (yellow region) [31] and the 3 years HESE (green points) [12].

On the whole sky, the diffuse Galactic emission computed with the KRA$_\gamma$ model can only account up to $\sim 15\%$ (to be compared to $\sim 8\%$ obtained for the conventional set-up) of the flux measured by IceCube. Clearly an extra-Galactic (EG) contribution must be invoked to account for all IceCube event as well as for their almost isotropic distribution. Here we assume this EG component to be isotropic, as expected if it is of cosmological origin, and use the astrophysical muon neutrino IceCube measurements from the northern hemisphere [15] – where we found the Galactic emission to be only $\sim 1/10$ of the total flux – to probe its spectral properties. For illustrative purposes in the right panel of Fig. 2 we show the effect of adding to the IceCube best fit of $\Phi_{\nu_\mu}^{\rm North}$, multiplied by three to account for all flavors – as representative of the EG flux – the Galactic neutrino emission computed with the KRA$_\gamma$. While, under this hypothesis, the latter is not required to explain the observed full-sky flux, the emission computed with the KRA$_\gamma$ model helps to improve the fit in the low-energy part of the IceCube spectrum.

5. Conclusions

We showed that a Galactic CR model adopting a proper radial dependence for both the rigidity scaling index of the diffusion coefficient and the convective wind, which was proposed to reproduce Fermi-LAT results [5], also matches Milagro observations at 15 GeV. Since this model also satisfy γ-ray measurements in other sky windows, it provides the first consistent picture of the diffuse γ-ray emission of the Galaxy from few GeVs up to tens of TeVs. We used the same model to compute the Galactic neutrino emission and showed that it is significantly larger than that computed with conventional CR propagation models. Our results are in agreement with ANTARES upper limits and with the neutrino flux along the GP inferred from IceCube results.

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